Upper limit on the $\eta \to \pi^+\pi^-$ branching ratio with the KLOE detector.

The KLOE Collaboration

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Abstract

We have searched with the KLOE detector for the P and CP violating decay $\eta \to \pi^+\pi^-$ in a sample of 1.55×10^7 η's from the decay $\phi \to \eta\gamma$ of ϕ-mesons produced in e^+e^- annihilations at DAΦNE. No signal is found. We obtain the upper limit BR($\eta \to \pi^+\pi^-$)$< 1.3\times10^{-5}$ at 90% confidence level.

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The study of η decays provides an excellent laboratory for testing the validity of symmetries of the physical world. The decay $\eta \to \pi^+\pi^-$ violates both P and CP invariance. In the Standard Model, the reaction can proceed only via the weak interaction with a branching ratio of order 10^{-27} according to Ref.[1]. Higher branching ratios are conceivable either introducing a CP violation term in the QCD lagrangian through the so-called θ term (a branching ratio up to 10^{-17} can be obtained in this scheme compatible with the experimental limit on the neutron electric dipole momentum) or allowing a CP violation in the extended Higgs sector (in this case 10^{-15} can be reached) as described in Ref.[1]. The detection of this decay at any level accessible today would signal P and CP violation from new sources, beyond any considerable extension of the Standard Model. The best published previous result from a direct search for the η decay to $\pi^+\pi^-$ was obtained in 1999: $BR(\eta \to \pi^+\pi^-) < 3.3 \times 10^{-4}$ at 90% confidence level [2].

We present here the result of a direct search for this decay performed with the

KLOE experiment at the Frascati ϕ factory, DAΦNE, based on an integrated luminosity of 350 pb^{-1} collected in the years 2001 and 2002. DAΦNE is an e^+e^- collider working at the centre of mass energy of 1019.5 MeV, i.e., at the ϕ mass. ϕ mesons are produced nearly at rest in the laboratory. Beams in DAΦNE collide with a crossing angle of $\pi - 0.025$ rad. ϕ-mesons are therefore produced with a momentum $|\vec{p_\phi}| \sim 12.5$ MeV/c in the horizontal plane, directed towards the centre of the storage rings. The precise value of the ϕ momentum, together with the centre of mass energy and the beam spot position, is determined run by run using Bhabha scattering events.

The total cross section for $e^+e^- \to \phi$ is $\sim$3 μb. η mesons are copiously produced at a typical rate of $\sim$2 Hz through the radiative decay $\phi \to \eta\gamma$, which has a branching ratio of 1.3%. In the decay chain $\phi \to \eta\gamma \to \pi^+\pi^-\gamma$, the photon is monochromatic ($E_\gamma = 363$ MeV) and is emitted according to an angular distribution $dN/d\cos\theta_\gamma \sim (1 + \cos^2\theta_\gamma)$, where θ_γ is the polar angle of the emitted photon with respect to the beam line. The invariant mass of the $\pi^+\pi^-$ pair is equal to the η mass: $M_{\pi\pi}$=M_η=547.3 MeV.

The KLOE detector consists of a large-volume drift chamber [3] (3.3 m length and 2 m radius), operated with a 90% helium-10% isobutane gas mixture, and a sampling calorimeter [4] made of lead and scintillating fibres. The calorimeter consists of a cylindrical barrel and two endcaps providing a solid angle coverage of 98%. A superconducting coil surrounds the entire detector and produces a solenoidal field B=0.52 T.

Tracks are reconstructed in the drift chamber with a momentum resolution of $\sigma(p_\perp)/p_\perp < 0.4\%$. Clusters of energy deposits in the calorimeter are classified either as associated to charged tracks (charged pions, electrons or muons) or as isolated (photons, K_L). Photon energies and arrival times are measured with resolutions of $\sigma_E/E = 5.7\%/\sqrt{E(\mathrm{GeV})}$ and $\sigma_t = 54\mathrm{ps}/\sqrt{E(\mathrm{GeV})} \oplus 50$ ps; impact positions are measured with a resolution of a few centimetres. The readout granularity is 4.5×4.5 cm^2 in the plane transverse to the fibres, and is segmented in five layers along the particles direction. The trigger [5] is based on the detection of at least two energy deposits in the calorimeter above a threshold that ranges between 50 MeV in the barrel and 150 MeV in the endcaps. The higher machine background rates at small angle requires a higher threshold in the endcaps.

Samples of simulated events are obtained using the GEANFI [6] code based on GEANT: event generators for any specific final state, including decay dynamics and radiative corrections, are provided together with the detailed description of the geometry and the response of each sub-detector.

The decay chain $\phi \to \eta\gamma \to \pi^+\pi^-\gamma$ is searched for by selecting events with two tracks of opposite charge with a vertex near the e^+e^- interaction point and

one prompt photon matching the missing energy and momentum obtained from the $\pi^+\pi^-$ pair and the ϕ kinematic variables. The vertex is required to be inside a cylinder 20 cm long and 8 cm in radius, with axis parallel to the beam line, centred at the beam spot position. The polar angle θ_t of each track is required to satisfy $45° < \theta_t < 135°$. A prompt photon is detected as an energy cluster not associated to any track, with time of flight T_{cl}, distance from the beam spot position R_{cl}, and energy E_{cl} satisfying the condition $|T_{cl} - R_{cl}/c| < 5\sigma_t(E_{cl})$, where σ_t is the energy-dependent time resolution. In order to match the missing energy and momentum obtained from the $\pi^+\pi^-$ pair with the photon kinematics, the angle ψ between the direction of the missing momentum and the direction of the photon is required to be less than 0.15 rad.

Each track is extrapolated to the calorimeter and is required to be associated with a calorimeter cluster. A major source of background is due to radiative Bhabha events, $e^+e^- \to e^+e^-\gamma$. Rejection of these events is based on the shower energy deposition in the calorimeter, on the time of flight, which is different for electrons and pions, and on kinematics. A likelihood estimator is constructed using the following information: the total energy of the cluster and the maximum energy release among the five planes of the calorimeter; the energy release in the first and in the last fired calorimeter plane; and $|T_{cl} - L/c|$, where L is the track length from the interaction point to the centroid of the cluster. The probability density function for each variable is obtained using samples of unambiguously identified pions from $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-$ events. The separation between $\pi^+\pi^-\gamma$ and $e^+e^-\gamma$ events based on the values of the likelihood estimators L_+ and L_- for positive and negative particles is shown in Fig. 1.

$\mu^+\mu^-\gamma$ and residual $e^+e^-\gamma$ events are rejected using the so called *track-mass* variable M_T. M_T is the particle mass computed assuming the ϕ decays to two particles of identical mass plus a photon. M_T is given by:

$$|\vec{p}_\phi - \vec{p}_1 - \vec{p}_2| = E_\phi - \sqrt{p_1^2 + M_T^2} - \sqrt{p_2^2 + M_T^2} \tag{1}$$

where $\vec{p}_1$ and $\vec{p}_2$ are the three-momenta of the two pions and E_ϕ and $\vec{p}_\phi$ are the total centre-of-mass energy and momentum respectively. The track mass value is obtained from tracking information only and is very weakly correlated to the likelihood estimator value. The requirement $129 < M_T < 149$ MeV selects $\pi^+\pi^-\gamma$ events; see Fig. 2. This cut, together with the cut on ψ described above, ensures that background due to $\phi \to \pi^+\pi^-\pi^0$ events is negligible.

The $M_{\pi\pi}$ spectrum of the selected events ranges from $2m_\pi$=279 MeV to M_ϕ=1019.5 MeV. Apart from the hypothetical signal, the physical processes which give $\pi^+\pi^-\gamma$ final states are $e^+e^- \to \pi^+\pi^-$ accompanied by ISR (initial state radiation) or FSR (final state radiation), $\phi \to f_0(980)\gamma$ with $f_0(980) \to$

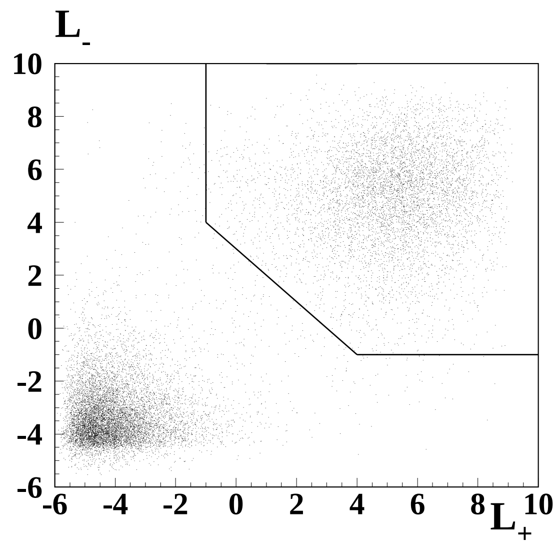

Fig. 1. Scatter plot of the likelihood variable for positive (L_+) and negative (L_-) particles in arbitrary units. The line is the cut applied to select pion and muon pairs (above) from electron pairs (below).

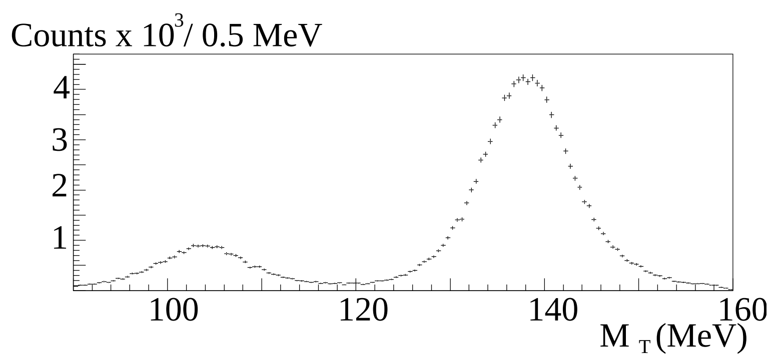

Fig. 2. Distribution of the *track mass* variable M_T showing the separation between the peaks due to $\pi^+\pi^-\gamma$ events (right peak) and to $\mu^+\mu^-\gamma$ events (left peak).

$\pi^+\pi^-$ and $\phi \to \rho^\pm\pi^\pm$ with $\rho^\pm \to \pi^\pm\gamma$. Analyses of the full spectrum in different photon angular ranges are reported elsewhere [7,8]. Here we are interested in the $M_{\pi\pi}$ region around the η mass where the signal is expected to be. The η mass region (500 - 600 MeV) of the $M_{\pi\pi}$ spectrum is dominated by ISR events with the radiated photon mostly at small polar angle. To reduce the amount of such events while keeping a reasonable acceptance, we require the photon to be at large angle ($45^\circ < \theta_\gamma < 135^\circ$).

From Monte Carlo simulation we find the overall signal efficiency to be, ϵ_s=(16.6$\pm$0.2$_{\rm stat}\pm$0.4$_{syst}$)%. The 2% systematic uncertainty is estimated by

comparing the data and Monte Carlo distributions of the variables M_T and ψ. The overall rejection factors for the backgrounds range between order 10^4 for $\mu^+\mu^-\gamma$ and 10^6 for $\pi^+\pi^-\pi^0$ and $e^+e^-\gamma$.

The expected $M_{\pi\pi}$ distribution for a possible signal is a Gaussian with a resolution of 1.33 MeV. Analysis of the similar and abundant decay $K_s \to \pi^+\pi^-$ shows that the Monte Carlo correctly reproduces the observed mass distribution (see Ref. [6]). Figure 3 shows the measured $M_{\pi\pi}$ spectrum in the

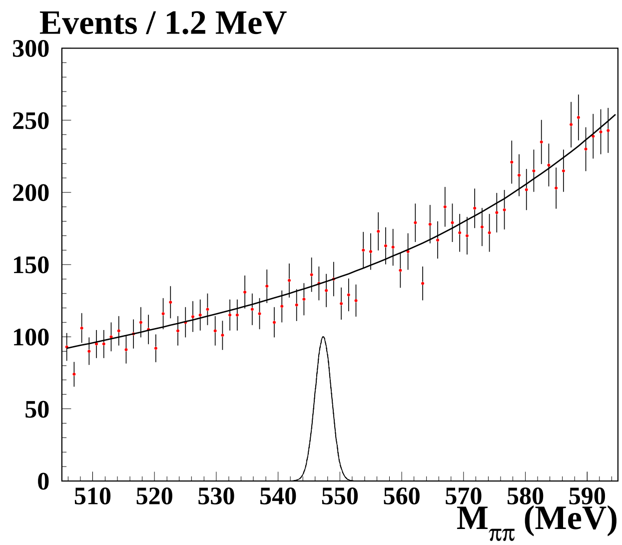

Fig. 3. $\pi^+\pi^-$ mass spectrum between 500 and 600 MeV superimposed to the fitted background. The Gaussian is the expected signal shape in arbitrary units.

region around the η mass, in 1.2 MeV bins, together with the expected form for the signal. No evidence for the signal is observed. The curve superimposed to the data is the result of a fit to the $M_{\pi\pi}$ spectrum over a much wider interval, from 410 MeV up to 1010 MeV with a function that describes all the appropriate physical processes:

$$\frac{\mathrm{d}\,N}{\mathrm{d}\,M_{\pi\pi}} = \left(\frac{\mathrm{d}\,\sigma(ISR)}{\mathrm{d}\,M_{\pi\pi}} + \frac{\mathrm{d}\,\sigma(FSR + f_0)}{\mathrm{d}\,M_{\pi\pi}} + \frac{\mathrm{d}\,\sigma(\rho\pi)}{\mathrm{d}\,M_{\pi\pi}} \right) \times \mathcal{L} \times \epsilon(M_{\pi\pi}). \qquad (2)$$

In Eq. 2 above, $\mathcal{L}$ is the integrated luminosity of the sample analysed, $\epsilon(M_{\pi\pi})$ is the selection efficiency as a function of $M_{\pi\pi}$ for the full range of the fit, and the $\mathrm{d}\,\sigma/\mathrm{d}\,M_{\pi\pi}$ terms are the differential cross sections for the various processes which contribute to the background. The fit has 7 free paramaters and gives a χ^2 value of 75 for 84 data points in the 500 - 600 MeV region and a value of 539 for 488 data points in the full mass range. 4 out of the 7 parameters describe the pion form factor according to Ref.[9]: M_ρ, Γ_ρ, α and β; the other 3 describe the scalar contribution according to Ref.[10]: M_{f_0}, g_{f_0KK} and $g_{f_0\pi\pi}$. The result of this fit does not change if we remove the data points in the signal

region. We use this result as the estimate of the background magnitude in the following.

In order to determine an upper limit for the branching ratio, we have repeated the fit by adding to the previously estimated background a signal component represented by a Gaussian with fixed mean and width of 547.3 and 1.33 MeV respectively, and free absolute normalisation. The fit returns a number of signal events $N_s = -8 \pm 24$, compatible with zero. The result does not depend on the choice of the fit interval and bin size. The probability distribution of N_s has been checked by generating a large number of histograms according to the background distribution and fitting each of them to get N_s. The results of this simple simulation show that N_s, in the case of no signal, is indeed Gaussian distributed with a mean compatible with zero and a width of 24. The 90% confidence-level upper limit on the number of events is obtained using the tables in Ref. [11]. We find $N_s < 33$.

Alternatively, we have used a polynomial parametrisation of the background, obtained by fitting the sideband regions (500 - 540 MeV and 555 - 600 MeV) only. Applying the same procedure to get N_s, we obtain $N_s = -10 \pm 24$ and consequently $N_s < 31$. The systematic uncertainty due to the parametrisation of the background is small and we use the largest value for the limit.

The total number of η's in the sample, N_η, is evaluated counting the number of $\phi \to \eta\gamma$ events with $\eta \to 3\pi^0$. The efficiency for this channel is $\epsilon(\phi \to \eta\gamma, \eta \to 3\pi^0) = 0.378 \pm 0.001_{stat} \pm 0.008_{syst}$, where the 2% systematic error is dominated by the uncertainty on the detection efficiency of low energy photons. Using the known branching fraction BR($\eta \to 3\pi^0$)=0.3251±0.0029 [12] we obtain:

$$N_\eta = \frac{N(\eta \to 3\pi^0)}{\epsilon(\phi \to \eta\gamma, \eta \to 3\pi^0) \times BR(\eta \to 3\pi^0)} = 1.55 \times 10^7 \tag{3}$$

with a systematic uncertainty due to the knowledge of the efficiencies and of the intermediate branching ratio of 2%.

Taking the result $N_s < 33$, the 90% confidence-level upper limit is

$$BR(\eta \to \pi^+\pi^-) = \frac{N_s}{N_\eta \epsilon(\eta \to \pi^+\pi^-)} < 1.3 \times 10^{-5}. \tag{4}$$

This result is the best obtained to date and is 25 times more stringent than the previous best limit.

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